Enhancing AUV Operational Capabilities: Hovering, Rendezvous, and Docking.

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1   LONG-TERM GOALS

This proposal describes a program of work designed to contribute to the Navy's capabilities in mastering the mine warfare problem by providing AUV hovering, rendezvous, and docking capability in modular reconfigurable AUVs. These enhanced maneuvering capabilities will extending mission durations, enable stormy weather operations, and provide station keeping abilities for imaging and intervention tasks. The significant activity associated with bottom sediment transport occurs during the energetic sea states associated with inclement weather. Furthermore to extend the duration of AUV reconnaissance missions, docking for recharge and data upload is necessary.

2   OBJECTIVES

One of the goals of the AOSN is to achieve extended duration (2 week) missions from AUVs, mine reconnaissance, rapid environmental assessment, surveillance, and adverse weather missions would all benefit greatly from multi-day capability. One way to achieve extended duration missions is to dock and recharge batteries and off-load data.

An important mission is to observe the dynamics of the ocean environment during the passage of a storm front.Because surface ships are precluded from operation during a storm passage it is difficult to make measurements of the dynamics during the fronts passage. Hence, models of sediment re-suspension and mine like object burial rates must be made on extrapolations of levels days later. This project and companion projects are developing many of the enabling technologies necessary for cold front passage measurement. Since storm front disturbances are substantially reduced below the surface, an AUV could be used to measure in-situ events during the front's passage. However, the AUV must be inserted during calm weather, sleep on the bottom, awake and sample during the storm front, and then go back to sleep until calm weather permits its recovery. This is best done if the AUV can dock and therefore be constrained until it needs to operate.

The utility of AUVs in shallow water search and survey operations is enhanced by multiple vehi-

	Report Documentation Page		Form Approved OMB No. 0704-0188

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1. REPORT DATE **30 SEP 1997**	2. REPORT TYPE	3. DATES COVERED **00-00-1997 to 00-00-1997**	
4. TITLE AND SUBTITLE **Enhancing AUV Operational Capabilities: Hovering, Rendezvous, and Docking**		5a. CONTRACT NUMBER	
		5b. GRANT NUMBER	
		5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)		5d. PROJECT NUMBER	
		5e. TASK NUMBER	
		5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Florida Atlantic University,Department of Ocean Engineering,777 Glades Road,Boca Raton,FL,33431**		8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)	
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)	

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

cle operations this enables synoptic data collection and high coverage rates. A major objective of this project is to design and build the next generation modular mini AUV with reduced cost of manufacture, maintenance, and operation at similar levels of capability to the current generation of AUVs.

3   APPROACH

Docking:— The modular nature of the OEX provides tremendous reductions in the time required to reconfigure the vehicle for different missions. This is accomplished by placing all the mission specific sensors in a mid and nose cone section dedicated for payloads. The components needed to operate the vehicle, such as propulsion, navigation, energy, and control are grouped in the tail section. Putting docking components in the nose violates this separation and would substantially reduce vehicle reconfigurability. Hence, our approach is to use a belly mounted stinger that couples with sea bottom dock. The docking system navigation is based on a low cost high precision commercial SBL/LBL system. The SBL is mounted on a portable collapsible rigid SBL array. This will provide a portable low-cost docking system. The docking mechanism can be described as a 4 leaf clover with a spring loaded latch at the center. The the puck catches under the edge of one of the leaves and is directed to the center where the leaves attach. Once latched, power recharge through a direct connection to the bottom of the puck and data transfer through RF antennas in the puck and clover is accomplished

FAU has developed a full 6 DOF nonlinear simulation program for AUVs. Based on this simulation an intelligent docking controller has been developed that can dock an AUV to either a moving or stationary target. This controller uses fuzzy logic rules to determine desired direction and speed. The fuzzy rules make provision for the docking environment such as the location of nearby objects and the bottom. Comparable approaches to path planning in the presence of known obstacles such as potential fields are much more computationally expensive. Essentially, the fuzzy rules define a vector flow field for vehicle motion. Precision increases as the vehicle approaches the target.

Modular Mini AUV:— The new mini AUV design is ultra modular with easy connectable plastic molded pressure vessels and cabling systems. Innovative features of this design include exterior fared cable channels that allow reordering of pressure vessels without any interior rewiring and an octagonal cross section high strength micro fiber reinforced injection molded plastic pressure vessel that minimizes configuration and maintenance costs. Each pressure vessel acts as a fared hull section. Each section is 12" long and 8.5" from side to side.

Hover Capability:— Hover capability will be added to the new mini modular AUV by the construction of two cross body tunnel thruster sections. This will be two of the modular hull/pv sections that have been each outfitted with a vertical and horizontal thruster. This will make hovering capability a removable option for any of the new mini AUVs built in the future. The tunnel thrusters will have 3" diameter propellers. The control system is parametrized so that inclusion of thrusters can be accounted for automatically. FAU will use its simulation facilities and collaborative efforts with NPS to develop the hovering controllers.

Obstacle avoidance capability will be based on inexpensive single and multi-beam sonars.

4   WORK COMPLETED

The "Divetracker" SBL system has been acquired and integrated into the vehicle. The portable

dock has been built. It is easy to deploy taking only a few minutes. Extensive at sea tests of the SBL system have been conducted both stationery and with a free swimming AUV. The SBL have some manufacturing flaws that caused crosstalk on the receive channels. Diagnosing and correcting this problem took several weeks.

A prototype docking "cloverleaf" has been built and pool tests have been conducted with an AUV body and stinger. The pool tests tested a full range of approach angles and speeds. The basic concept was proven but did not always capture for off center approach angles. worked Based on the results of these tests a new redesigned version of the docking mechanism is under construction. The redesign addresses the problems in the prototype and will be used for at sea trials. A stinger retraction mechanism has been designed that is based on the same mechanism used for the pop up DGPS antennae but turned upside down.

A transformer coupled power transfer mechanism was researched but discarded because the size of transformers required would make the puck and stinger too large. Instead a simpler power transfer mechanism was designed and successfully tested. This method uses a spring loaded button on the dock that plunges into the bottom of the puck. A rubber sheath insulates the end of the button from the seawater and the exposed current return path on the top of the puck. Tests were conducted to determine the life span of the electrode should the sheath fail.

Data transfer tests were conducted in saltwater between two loop antennae to determine the maximum separation distance for reliable communications. Simulations of the docking controller were conducted using 6 DOF coefficients obtained from VCT.

The pressure vessel for the new mini modular AUV has been designed and the mold has been ordered. A consultant engineer who specializes in injection molding was contracted to help with the design. Also designed for molding is the nose cone. The tail section will be machined and will use a similar design to the redesign of the OEX gear box. Those two" systems are being co-designed for the sake of economy. The sensor systems are being specified and acquired. The computer control system on the new mini-auv will be based on LonWorks for the low level system. The VME system used in the Ocean Explorer will not be used in the new vehicle. Heavy computation functions such as navigation and logging will be done with PC-104+ or Compact PCI computers. We have acquired a PC-104+ based computer and have begun the process of familiarization of porting of our code.

The small size of the thrusters required for the mini AUV meant that we could not obtain commercial off the shelf units. We had to design our own. Several different small size thrusters concept prototypes were built and tested in our tank with a load cell. These include chain driven, direct drive, and right angle gear. We found the right angle gear approach to be the best combination of efficiency and size. Two sizes (4" and 3") were tested at Johns Hopkins University with the aid of John Witcomb. Each size was tested with both single and double propeller versions. Several hundred megabytes of test data were generated to quantify the performance. This data will be the basis of a master's thesis. Based on the results of these tests a thruster configuration is currently being designed.

A pencil beam sonar and the Interphase phased array sonar have been acquired and tested. The pencil beam sonar has been integrated into the vehicle. Extensive hardware in the loop simulation tests of the obstacle avoidance controller have been conducted and are the basis of a master's thesis. The system will be tested at sea at the next reasonable opportunity. Modifications to the Interphase phased array "fish finder" sonar have been specified and ordered. These will provide an RS-

232 output of range and bearing. Once the modified units are delivered they will be integrated into the AUVs and used for either obstacle avoidance or a multi-beam bathymetric sonars.

5   RESULTS

The at sea test of the dive tracker confirm that it measures vehicle position when stationary to less than +- 6 inches rms. However this accuracy degrades rapidly when the vehicle is moving faster than 0.3 knots. This is generated by the particular pinging protocol. A modified version of the SBL with an LBL pinging protocol has been ordered to address this problem. It is expected that the new system will measure position to within +- 3 rms for stationary vehicles. With the vehicle computing its position between fixes with its on board DVL and compass the new system should calculate position to within +- 6" rms for motion up to 3 knots. Successful pool tests of an AUV body with stinger attached being successfully captured by the dock. Once the final version of the dock is completed at sea AUV trials will commence.

Test show the copper electrodes will survive over 9 hours of exposed operation for power transfer. Fully sheathed electrodes show no perceptible corrosion. Gold plated titanium electrodes should have several times the life of the copper. But even copper will allow multiple failure attempts at power transfer initiation. Test showed that a 900 mHz carrier would reliably transmit data as far as 9 inches in saltwater. The separation between the stinger and dock antennas is less than half that distance.

The thruster tests show that reasonably efficient thrusters can be built for small diameter tunnels.

An outlier filter was developed and tested to suppress erroneous ranges from the obstacle avoidance sonar. The filter used past returns and vehicle motion estimates to calculate a window of acceptable values. The obstacle avoidance controller simulation is able to avoid bottom, mid-water column, and surface obstacles. The controller acts as a behavior that is smoothly combined with the heading and depth controllers to guide the vehicle around obstacles and then return it to its original path.

6   IMPACT/APPLICATIONS

Docking capability will enable the OEX and any of its modular payload sections to achieve extended mission durations. This makes possible certain types of sampling that have never before been successful such as adverse weather missions. Currently no other small size AUV provides that combination of the selection of mission payloads and extended mission duration. The mini auv will lead to greatly reduced costs of development, integration, operation, and maintenance. This would provide a modular reconfigurable vehicle in the same size range as the REMUS. A full spectrum of AOSN and mine reconnaissance tasks could be accomplished cost effectively using this platform.

7   TRANSITIONS

Several payloads are currently under development that will benefit from docking and hover capability.

8   RELATED PROJECTS

AUV Navigation and Self-Motion in Shallow Water, ONR.

Autonomous Oceanographic Sampling Network Development, ONR.

Enhancing AUV Operational Capabilities, ONR.

Synoptic Data Collection With Multiple AUVs, ONR.

ACOMS Acoustic Communication between UUV and Submarine, ONR ATD.

ONR MURI on Nonlinear Control

University of Miami RSMAS (Proposed NSF), University of Hawaii (Proposed NSF)

USF Projects, CoBop, UK Autosub, WHOI Remus, MIT Odyssey

Advanced Machinery Control Architecture (ACMA) Laboratory Development for Automated Navy Ship Auxiliary System Control, Reconfiguration and Failure Recovery, ONR.

Dependable Network Topologies with Network Fragment Healing for Component Level Intelligent Distributed Control Systems for Naval Shipboard Automation, ONR.

9 REFERENCES

[1] Charbel G. Rizk and Samuel M. Smith, "Automatic Design of Nonlinear Controllers with Optimal Global Performance Using Best Estimate Directed Search and Continued Propagation Cell Mapping", submitted to IEEE Transactions on Systems Man and Cybernetics 1997.

[2] P.E. An, S.M. Smith, An Experimental Database of the Ocean Explorer AUV for Self-Motion Controlled Study, submitted to the IEEE Transactions on Oceanic Engineering, 1997.

[3] S.M. Smith, K. Ganesan, P.E. An, & S.E. Dunn, "Strategies for Simultaneous Multiple AUV Operation and Control", *International Journal of Systems Science*, in Press.

[4] P.E. An, S.M. Smith, S.E. dunn, X. Chen, & L. Mu, "New Experimental Results on Shallow-Water Autonomous Underwater Vehicle Motion in Controlled Environments," 7th International Offshore and Polar Engineering Conference, ISOPE-97, May 25-30, 1997, Honolulu Hawaii.

[5] Submesoscale Coastal Ocean Dynamics Using Autonomous Underwater Vehicles and HF Radar, submitted to American Meterological Society Conference, 1998

[6] Hafen, M., Hine, A., Naar, D., 1997, Correlating geophysical, sedimentary and hydrologic characteristics of two areas of carbonate-siliciclastic sand-ridges on Florida's Gulf Coast: Abstracts of the American Geophysical Union National Meeting, San Fransisco, December, 1997.

[7] Mallinson, D., Naar, D., Hine, A., Hafen, M., Schock, S., Smith, S., Kloske, J., Gelfenbaum, G., Wilson, D., Lavoie, D., Richardson, M., 1997, Acoustic seafloor mapping using the AUV Ocean Explorer: Proceedings of the 10th International Symposium on Unmanned Untethered Submersible Technology.

[8] Mallinson, D., Locker, S., Hafen, M., Naar, D., Hine, A., Lavoie, D., Schock, S., 1997 (in press), A high resolution geological and geophysical investigation of the Dry Tortugas carbonate depositional environment: Geo-Marine Letters, v. 17.

[9] Mallinson, D., et al., 1997, Evaluating the acoustic remote sensing capabilities of the autonomous underwater vehicle Ocean Explorer: Abstracts of the American Geophysical Union National Meeting, San Fransisco, December, 1997.

[10] Mallinson, D., Hafen, M., Hine, A., Locker, S., 1997, The shallow subsurface geology of the Greater Tortugas area: Key West Campaign Workshop, Naval Research Laboratory, Stennis Space Center, MS.

[11] P.E. An, S.M. Smith, J. Park, A.J. Healey, Asynchronous Data Fusion for AUV Navigation Via Heuristic Fuzzy Filtering Techniques, Oceans 97 Conference, Vol.1, pp.397-402, Nova Scotia, Canada, October, 1997

[12] X. Chen, D. Marco, S. Smith, P.E. An, K. Ganesan, T. Healey, Six DOF Nonlinear AUV Simulation Toolbox, Oceans 97, Vol.2, pp.1070-1074, Conference, Nova Scotia, Canada, October, 1997.

[13] S.M. Smith*, S. McPhail**, A. Healey***, R. Russell, LONTalk as a Standard Protocol for Underwater Sensor Platforms, Oceans 97, Conference, Nova Scotia, Canada, October, 1997.

[14] J. Park, S. Smith, A. Neel, A Peer-to-Peer Communication Protocol for Underwater Acoustic Communication, Oceans 97, Conference, Nova Scotia, Canada, October, 1997.

[15] S.M. Smith*, A. Healey, and D. Kronen,Experimental Results of an Inexpensive Short Baseline Acoustic Positioning System for AUV Navigation, Oceans 97, Conference, Nova Scotia, Canada, October, 1997

[16] S.M. Smith, P.E. An, K. Ganesan, J. Park, & S.E. Dunn, "Design and Applications of Field Reconfigurable Autonomous Underwater Vehicles", Underwater Intervention Conference, February 17-19, 1997, Houston Texas.

[17] C. Vasudevan, K. Ganesan, S.M. Smith, "Collision Avoidance by Dynamic Path Selection and Fuzzy Behavior Control",   IEEE Transactions on Robotics and Automation, (submitted)

[18] Samuel M. Smith, Modular UUV Architectures: Structure, Control, and Power; Issues and Experiences. SOC UUV Showcase and Exhibition, Southhampton UK, Sept 24-25, 1997

[19] D. M. Kronen, S. M. Smith*, J. C. Frankenfield, K. Bryan, R. T. Dunn, Introduction to the Docking Facility of the Ocean Explorer Series Autonomous Underwater Vehicles, UUST 97, Durham New Hamshire, Sept 1997.

[20] Betzer, P.R., S.E. Dunn, S.M. Smith, R.H. Byrne, K.L. Carder, P.G. Coble, D.K. Costello, K.A. Fanning, and T.L. Hopkins. 1996. Sediment-Water Interactions on Continental Shelves. Presented at AGU Ocean Sciences Meeting, San Diego, California, 12-16 February1996.

[21] Peacock T.G., D.K. Costello, K.L. Carder, T. Carney, and J. Kloske.

[22] A new Vessel for Support of Unmanned Underwater Vehicle Operations.

[23] Abstract Submitted to 1998 AGU Ocean Sciences Meeting.

[24] Charbel Rizk, Best Estimate Directed Search and Continued Propagation Cell Mapping for Optimal Control, FAU PHD Dissertation August 1997.

[25] Kevin White, "Design and Implementation of an Altitude Flight Controller for the FAU Ocean Voyager II", FAU Masters Thesis(April 96).

[26] Thomas C. Flanigan, Development and Analysis of Real Time Software for Autonomous Underwater Vehicles, FAU Masters Thesis.

[27] S. M. Smith, P. E. An, D. Kronen, K. Ganesan, J. Park, S. E. Dunn, "The Development of Autonomous Underwater Vehicle Based Survey and Sampling Capabilities for Coastal Exploration", Oceans 96, Ft. Lauderdale, FL, September, 1996.

[28] P. E. An, A. J. Healey, S. M. Smith, S. E. Dunn, "New Experimental Results on GPS/INS Integration Using Ocean Voyager II AUV", IEEE AUV 96, pp.249-255, Monterey, CA, June, 1996.

[29] K. Ganesan, S.M. Smith, K. White, & T. Flanigan, "A Pragmatic Software Architecture for UUVs", IEEE AUV 96, pp., Monterey, CA, June, 1996.

[30] Ken Holappa, Manhar Dhanak, Samuel Smith and Edgar An, "Ocean Flow Measurement Using and Autonomous Underwater Vehicle" IEEE AUV 96, pp. 424-428, Monterey, CA, June, 1996.

[31] K.A. White, S.M. Smith, K. Ganesan, D. Dronen, G.J.S. Rae & R.M. Langenbach, "Performance Results of a Fuzzy Behavioral altitude Flight Controller and Rendezvous & Docking of an Autonomous Underwater Vehicle with Fuzzy Control", IEEE AUV 96, pp., Monterey, CA, June, 1996.

[32] S. M. Smith, K. Ganesan, S. E. Dunn, P. E. An, "Strategies for Simultaneous Multiple AUV Operation and Control", IARP96, France, April, 1996.

[33] Min Xu, " High Performance and Robust Control" Ph.D. Dissertation Florida Atlantic University College of Engineering, April 1996.

[34] P. E. An, S. M. Smith, S. E. Dunn, "A Quantitative Measure of Sea-State Effect on Small Autonomous Underwater Vehicle Motion in Shallow Water", Oceanlogy International 96, pp.211-233, Brighton, U.K., March, 1996.

[35] S. M. Smith, S. E. Dunn, P. E. An, "Data Collection with Multiple AUVs for Coastal Oceanography", Oceanology Interational 96, pp.263-279, Brighton, U.K., March, 1996.

[36] C. Vasudevan and K. Ganesan, "Case-Based Path Planning for Autonomous Underwater Vehicles", Autonomous Robots Journal Vol 3, pp. 79-89, 1996.

[37] P.R. Betzer, S.E. Dunn, S.M. Smith, R.H. Byrne, K.L. Carder, P.G. Coble, D.K. Costello, K.A. Fanning. T.L. Hopkins, "Sediment - Water Interaction on Continental Shelves." American Geophysical Union 1996 Ocean Sciences Meeting.